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Kaluza-Klein dipoles, brane/anti-brane pairs and instabilities

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ABSTRACT

We discuss brane/anti-brane systems by constructing dipole solutions in arbitrary dimension. A detailed illustrative example is worked out for six dimensions. We generalise these solutions by exciting extra gauge fields and generate new solutions by applying various duality transformations on them. Finally an argument is presented on the tachyonic instability by analysing the string fluctuations on the dipole background.

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1. Introduction

Brane/anti-brane pairs have recently played very important role in our understanding of stable non-BPS states in string theory [1]. As a classical vacuum, brane/anti-brane pair leads to unstable configuration. First of all, they attract each other as they are oppositely charged. Moreover, when the separation between them is of the order of the string length, there appears tachyon in the configuration [2]. However, it has been argued in the recent past that, in certain cases, this tachyon leads the system to a stable fixed point in the renormalisation group sense.

Since the classical force between brane/anti-brane system never vanishes, search for a configuration describing the pair as a classical solution looses its meaning. However, if we introduce a non-zero background electromagnetic field which triggers repulsion between brane and the anti-brane in such a way that it cancels the attractive force between them, then one would expect to find a classical configuration describing the pair in equilibrium[3]. In [3], such a solution was constructed in string theory and various instabilities were analysed. It has been argued that the Kaluza-Klein (KK) dipole of 5-dimensional gravity [4] has the property of describing brane/anti-brane pair when we add required flat directions[4]. An asymptotic magnetic field appears naturally which, in turn, keeps the system in equilibrium. To our knowledge, this is the only classical configuration known for the brane/anti-brane system till now.

Before we go into the detail of our analysis of brane/anti-brane pair let us first summerise what we do in this letter. In the first part of this letter, we construct the brane/anti-brane pair without adding flat directions to the 5-D dipole. This can easily be done as follows. 5-D KK dipole [4] follows from 4-D Euclidean Kerr black hole after adding a time direction. However, from [7], we know Kerr black hole solutions in any dimension. Thus following the above prescription, one would expect to get dipole configurations in any dimension. In suitable coordinate system it is possible to isolate the brane or the anti-brane that makes up the dipole. The number of world-volume directions depends on the space-time dimensions of this dipole. Interestingly enough, in this coordinate system (which isolates brane/anti-brane), some of

[3]It may not be a stable equilibrium though. Instabilities due to the tachyon is expected to be absent if the distance between the pair is large enough.

[4]On the other hand, some of the dipole like solutions with magnetic flux tubes have directly been constructed in [5, 6]. However, most of them do not have KK interpretation.

the transverse directions of the original Kerr-metric translate into the world-volume directions of the brane and anti-brane. As an illustrative example, in the next section we discuss such a pair in 6 dimensions. We also discuss various benefits of constructing brane/anti-brane pairs this way (rather than starting with 5-D dipole and adding flat directions). For example, it is easy to excite the world-volume gauge fields on such a pair. Furthermore, we discuss how, using various conjectured duality symmetries of string theory, one can construct other brane/anti-brane pairs from the original. In the last section, we try to understand if these brane/anti-brane configurations (in the presence of background electromagnetic filed) can be realised as stable string or superstring background at least when the distance between constituents is large. Unfortunately, we find that they likely lead to unstable string backgrounds. A string or superstring propagating in these background contains tachyon in their spectrum.

2. Construction of KK dipoles

In order to construct the dipole solution in D dimensions[5], we start with the $(D-1)$-dimensional Kerr metric [7]:

$$\begin{aligned} dS^2_{(D-1)} &= -\frac{r^2 + a^2\cos^2\theta - 2Mr^{6-D}}{r^2 + a^2\cos^2\theta}\, d\tau^2 - \frac{4Mr^{6-D}a\sin^2\theta}{r^2 + a^2\cos^2\theta}\, d\tau d\phi \\ &+ \frac{\sin^2\theta}{r^2 + a^2\cos^2\theta}\Big[(r^2 + a^2)(r^2 + a^2\cos^2\theta) + 2Mr^{6-D}a^2\sin^2\theta\Big]\, d\phi^2 \\ &+ \frac{r^2 + a^2\cos^2\theta}{r^2 + a^2 - 2Mr^{6-D}}\, dr^2 + (r^2 + a^2\cos^2\theta)\, d\theta^2 + r^2\cos^2\theta\, d\Omega^{D-5}. \end{aligned} \tag{1}$$

Note that this metric has horizon(s) when

$$r^2 + a^2 - 2Mr^{6-D} = 0. \tag{2}$$

For $D \leq 6$, there is a critical value of a beyond which the horizon does not exists. However, in case of $D > 6$, for any a and M, there exists one horizon.

[5]This is similar to the construction of Gross-Perry dipole [4] for $D = 4$ and is also discussed in [8] in different context

To construct the KK dipole in D dimensions, we perform an Euclidean rotation

$$\tau \to -iX, \qquad a \to ia, \tag{3}$$

and add a new time direction t. The solution thus obtained has the following form:

$$\begin{aligned} dS^2 &= -dt^2 + (r^2 - a^2\cos^2\theta)(\frac{dr^2}{\Delta} + d\theta^2) + \Delta\ \sin^2\theta\ \mathcal{H}\ d\phi^2 \\ &\quad + \mathcal{H}^{-1}\ (dX - A_\phi d\phi)^2 + r^2\cos^2\theta\ d\Omega^{D-5}, \end{aligned} \tag{4}$$

where the gauge field A_ϕ and the functions $\mathcal{H}$ are given by:

$$\mathcal{H} = \frac{r^2 - a^2\cos^2\theta}{\Delta + a^2\sin^2\theta}, \qquad A_\phi = \frac{2Mr^{6-D}a\ \sin^2\theta}{\Delta + a^2\sin^2\theta}\ , \tag{5}$$

and

$$\Delta = r^2 - a^2 - 2Mr^{6-D}, \tag{6}$$

Since the solutions (2) and (4) are time independent, the above construction is guaranteed to give a solution of the Einstein equations and can be embedded in any theory containing gravity. The fact that this solution indeed corresponds to a monopole/anti-monopole bound state can be seen by looking at the near pole limit.

Here, instead of being general, we would look at (4) for $D = 6$, for reasons that will become clear later. The metric in 6 dimensions takes the form:

$$\begin{aligned} dS^2 &= -dt^2 + (r^2 - a^2\cos^2\theta)(\frac{dr^2}{\Delta} + d\theta^2) + \Delta\ \sin^2\theta\ \mathcal{H}\ d\phi^2 \\ &\quad + \mathcal{H}^{-1}\ (dX - A_\phi d\phi)^2 + r^2\cos^2\theta\ d\chi^2. \end{aligned} \tag{7}$$

where

$$\Delta = r^2 - a^2 - 2M\ , \qquad A_\phi = \frac{2Ma\sin^2\theta}{\Delta + a^2\sin^2\theta}\ . \tag{8}$$

To avoid the conical singularity at $r = \sqrt{a^2 + 2M}$, one must have

$$0 \le X \le \frac{4\pi M}{\sqrt{a^2 + 2M}}\ , \qquad 0 \le \phi - \frac{aX}{2M} \le 2\pi\ . \tag{9}$$

Notice that in the limit of large a, the radius in the X direction depends on the ratio $\frac{M}{a}$. This is unlike the dipoles in $D = 5$, where the radius along

X at large a is *independent* of a [3]. The very presence on this solution for arbitrary a and M itself suggests that the constituents that makes the dipole are in equilibrium. Due to this twisted boundary condition (9) on ϕ, there is an asymptotic magnetic field [8]. If we use $\psi = \phi - aX/2M$ as independent coordinate, the magnetic field is given by $B = a/2M$. [6]

To have further insights of the configuration, we will now analyse the metric at $\theta = 0, \pi$ when Δ vanishes. From the structure it is clear that the zero of Δ occurs at $r = r_0 = \sqrt{a^2 + 2M}$. To analyse the metric near $r = r_0,\ \theta = 0$, we define coordinates [7]

$$\sqrt{a^2 + 2M}\ \sin^2\theta = \tilde{\rho}\ (1 - \cos\tilde{\theta}), \tag{10}$$

$$2(r - r_0) = \tilde{\rho}\ (1 + \cos\tilde{\theta}), \tag{11}$$

and look at the limit

$$a \to \infty, \qquad M \to 0, \qquad \theta \to 0, \qquad r \to r_0 \tag{12}$$

with $a \sin^2\theta$ fixed and $r - r_0$ finite. In this limit, the metric takes the following form

$$dS^2 = -dt^2 + d\tilde{\chi}^2 + H^{-1}\Big(dX - A_\phi d\phi\Big)^2 + H\Big(d\tilde{\rho}^2 + \tilde{\rho}^2 d\tilde{\theta}^2 + \tilde{\rho}^2 \sin^2\tilde{\theta} d\phi^2\Big) \tag{13}$$

with

$$H = 1 + \frac{\tilde{M}}{\tilde{\rho}} \qquad A_\phi = \tilde{M}(1 - \cos\tilde{\theta}) \qquad \tilde{M} = \frac{M}{\sqrt{a^2 + 2M}} \tag{14}$$

In (13), $\tilde{\chi} = \sqrt{a^2 + 2M}\chi$ with period $0 \leq \tilde{\chi} \leq 2\pi\sqrt{a^2 + 2M}$. Thus we see that near $r = r_0,\ \theta = 0$, there is a six-dimensional KK anti-monopole structure. The solution can, in turn, be interpreted as a string like metric with world-sheet coordinates $t, \tilde{\chi}$. This anti-monopole has a mass given by $\tilde{M}$ which depends on both a and M [8]. Similarly, one can analyse at $r = r_0, \theta = \pi$. This gives a metric of a monopole configuration which has the same metric as (13) with a change of sign in the gauge field.

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[6] A different choice of coordinate will however change the magnetic field, see [8].

[7] This coordinate system turns out to be the analogous one that was used in [3] for the five-dimensional dipole.

[8] This is however unlike the case for $D = 4$. In this case one gets a anti-monopole near $r = r_0, \theta = \pi$ whose mass is *independent* of a [3].

We would now like to make a comment on the supersymmetry. The solution (4) is not a BPS-state and therefore breaks all supersymmetry, in spite of the fact that it is made out of two supersymmetric solutions. The reason for this is that each of the constituents breaks half of the supersymmetry, being precisely the half that the other constituents leaves unbroken. Overall the solution does not preserve supersymmetry. However in the near pole limit we get a supersymmetry enhancement.

3. New dipoles from dualities

Starting from the KK dipole solution (4), we can generate a new dipole solutions, acting on the first one by duality transformations. The dipole will transform under the dualities as each of its constituents, so that the interpretation of dual dipoles can be found from the transformation of each single pole. We will do our analysis also here in $D = 6$.

A first possibility is to perform a T-duality transformation on (4). As we have seen earlier, the radius along X asymptotically reaches to $\frac{M}{a}$ for large a. Since T-duality inverts the radius, the T-dual metric will have the co-ordinate X with very large radius. Furthermore, a single KK monopole goes under T-duality to a solitonic string $S1$ [9], so we expect the dipole (4) to go to an H-dipole or $S1$/anti$-S1$-configuration. The solution obtained after acting with T-duality in the X-direction is, in the string frame (see Fig. 1, in the conventions of [9]):

$$
\begin{aligned}
dS^2 &= -dt^2 + (r^2 - a^2\cos^2\theta)(\frac{dr^2}{\Delta} + d\theta^2) \\
&\qquad + \mathcal{H}\ dX^2 + \Delta\sin^2\theta\ \mathcal{H}\ d\phi^2 + r^2\cos^2\theta\ d\chi^2, \qquad (15)\\
B_{x\phi} &= \frac{2Ma\sin^2\theta}{\Delta + a^2\sin^2\theta} \qquad\qquad e^{-2\Phi} = \mathcal{H}^{-1}.
\end{aligned}
$$

It is not difficult to check that in the near pole limit (12) this configuration indeed takes the form of an $S1$-brane, oriented in the $\tilde{\chi}$-direction.

The special feature about six dimensions is the string/string duality [10], which relates the strongly coupled solitonic string to the weakly coupled fundamental string (see Fig. 1). Applying this duality to the previous solution

[9]This is the double dimensional reduction of the ten-dimensional solitonic five-brane $S5$, sometimes also called H-monopole.

$$\begin{tikzcd} D=10 & F1 \arrow[d] & S5 \arrow[r, no head, "T"] \arrow[d] & KK \arrow[d] \\ D=6 & F1 \arrow[r, dashed, no head, "S"] & S1 \arrow[r, no head, "T"] & KK \end{tikzcd}$$

Figure 1: *The relation between $D = 6$ and $D = 10$ solutions: Vertical arrows imply direct dimensional reduction over a four-torus, dotted lines S-duality and straight lines T-duality. The dipole solutions, consisting of a bound state of brane and anti-brane, transform under the various dualities as their separate components.*

(15) gives us the fundamental string/anti-string solution:

$$\begin{aligned} dS^2 &= \mathcal{H}^{-1}\Big\{-dt^2 + (r^2 - a^2\cos^2\theta)(\frac{dr^2}{\Delta} + d\theta^2) \\ &\qquad\qquad +\mathcal{H}\ dX^2 + \Delta\sin^2\theta\mathcal{H}\ d\phi^2 + r^2\cos^2\theta\ d\chi^2\Big\}, \qquad (16) \\ B_{x\phi} &= \frac{2Ma\cos^2\theta}{r^2 - a^2\cos^2\theta}\ , \qquad\qquad e^{-2\Phi} = \mathcal{H}, \end{aligned}$$

which reduces in the near pole limit to the fundamental string solution $F1$.

It is not difficult to lift these solutions up to ten dimensions: one only has to add extra directions by enlarging the solid angle $r^2\cos^2\theta\ d\chi^2$ to $r^2\cos^2\theta\ d\Omega^2$ and extend the dependence of $\mathcal{H}$ by taking for Δ the $D = 10$-form of (6). This is equivalent to constructing the KK-dipole directly in $D = 10$ and then generate the other dipole solutions by applying the ten-dimensional duality transformations.

The duality relations applied above are illustrated in Figure 1.

4. Exciting other gauge fields

In general, a D-dimensional Kerr black hole is characterised by $[\frac{D-1}{2}]$ angular momentum parameters [7], where the square brackets indicate the integer part. In order to obtain a dipole-like configuration with more then one non-trivial gauge field, we need to start with the general Kerr metric.

We illustrate this by starting with the Kerr metric in five dimensions with two non-zero angular momenta proportional to a_1 and a_2 [7]:

$$
\begin{aligned}
dS^2 &= -\frac{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta - 2M}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\tau^2 + \frac{r^2(a_1^2\cos^2\theta + a_2^2\sin^2\theta)}{(r^2 + a_1^2)(r^2 + a_1^2) - 2Mr^2} dr^2 \\
&+ (r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta) d\theta^2 + \frac{4Ma_1a_2\cos^2\theta\sin^2\theta}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\phi d\chi \\
&+ \frac{\sin^2\theta[(r^2 + a_1^2)(r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta) + 2Ma_1^2\sin^2\theta]}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\phi^2 \\
&+ \frac{\cos^2\theta[(r^2 + a_2^2)(r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta) + 2Ma_2^2\cos^2\theta]}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\chi^2 \\
&- \frac{4Ma_1\sin^2\theta}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\phi d\tau - \frac{4Ma_2\cos^2\theta}{r^2 + a_1^2\cos^2\theta + a_2^2\sin^2\theta} d\chi d\tau. \qquad (17)
\end{aligned}
$$

We then perform the same procedure (3) as before, and obtain the following metric:

$$
\begin{aligned}
dS^2 &= -dt^2 + (r^2 - a_1^2\cos^2\theta - a_2^2\sin^2\theta)\Big[\frac{dr^2}{\tilde{\Delta} + a_1^2a_2^2r^{-2}} + d\theta^2\Big] \\
&+ \frac{\sin^2\theta[(r^2 - a_1^2)(\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta) - 2Ma_1^2\sin^2\theta]}{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta} d\phi^2 \\
&+ \frac{\cos^2\theta[(r^2 - a_2^2)(\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta) - 2Ma_2^2\cos^2\theta]}{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta} d\chi^2 \\
&- \frac{4a_1a_2M\sin^2\theta\cos^2\theta}{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta} d\phi d\chi \\
&+ \frac{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta}{r^2 - a_1^2\cos^2\theta - a_2^2\sin^2\theta}\Big[dX - A_\chi d\chi - A_\phi d\phi\Big]^2 \qquad (18)
\end{aligned}
$$

with $\tilde{\Delta} = r^2 - a_1^2 - a_2^2 - 2M$ and

$$
A_\chi = \frac{2Ma_2\cos^2\theta}{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta}, \qquad A_\phi = \frac{2Ma_1\sin^2\theta}{\tilde{\Delta} + a_1^2\sin^2\theta + a_2^2\cos^2\theta}. \qquad (19)
$$

The general analysis of this metric is very complicated. We will restrict ourselves to the case $a_1 \gg a_2$. In this case, the metric structure simplifies and can be analysed in a straight forward manner. However, in doing so, we will miss out important physics which appear at order $\mathcal{O}(a^2)$ or higher.

In the limit $a_1 \gg a_2$, (18) reduces to the following simple form:

$$\begin{aligned} dS^2 &= -dt^2 + (r^2 - a_1^2\cos^2\theta)\Big[\frac{dr^2}{\Delta} + d\theta^2\Big] \\ &- \frac{4a_1a_2M\cos^2\theta\sin^2\theta}{\Delta + a_1^2\sin^2\theta}\, d\phi d\chi + \frac{\Delta\sin^2\theta(r^2 - a_1^2\cos^2\theta)}{\Delta + a_1^2\sin^2\theta}\, d\phi^2 \\ &+ r^2\cos^2\theta d\chi^2 + \frac{\Delta + a_1^2\sin^2\theta}{(r^2 - a_1^2\cos^2\theta)}(dX - A_\chi d\chi - A_\phi d\phi)^2, \end{aligned} \tag{20}$$

with $\Delta = r^2 - a_1^2 - 2M$ and

$$A_\chi = \frac{2Ma_2\cos^2\theta}{\Delta + a_1^2\sin^2\theta}, \qquad A_\phi = \frac{2Ma_1\sin^2\theta}{\Delta + a_2^2\cos^2\theta}. \tag{21}$$

In the near pole limit $r = r_0$ and $\theta = 0$ the metric reduces to

$$\begin{aligned} dS^2 &= -dt^2 + d\tilde{\chi}^2 + H(d\tilde{\rho}^2 + \tilde{\rho}^2 d\tilde{\theta}^2 + \tilde{\rho}^2\sin^2\tilde{\theta}d\phi^2) \\ &\quad -2\tilde{a}_2\tilde{M}(1 - \cos\tilde{\theta})\, d\tilde{\chi}d\phi \; + \; H^{-1}(dX - A_\phi d\phi - A_{\tilde{\chi}}d\tilde{\chi})^2 \end{aligned} \tag{22}$$

with the expression for the gauge fields given by:

$$A_\phi = \tilde{M}(1 - \cos\tilde{\theta}), \qquad A_{\tilde{\chi}} = \frac{\tilde{M}\tilde{a}_2}{\tilde{\rho}}. \tag{23}$$

Here the parameters $r_0, \tilde{M}$ have the same form as before with a replaced by a_1 and $\tilde{a}_2 = a_2/\sqrt{a_1^2 + 2M}$. This near pole limit suggests that the soliton at $r = r_0$ and $\theta = 0$ is an anti-monopole with a gauge field A_χ excited in the world volume direction, proportional to a_2. However it is not difficult to see that this extra gauge field breaks even in the near pole limit all of the supersymmetry.

In exactly similar manner, we can study the limit $a_2 \gg a_1$. In this case, the poles change the position, now located at $\theta = \pi/2$ and , $3\pi/2$ and the gauge fields interchange their roles. Obviously, making the duality transformations applied in Section 3, we can construct other brane/anti-brane pairs from (20).

5. Tachyonic Instability

All the solutions that are discused in (4) can be embedded obviously in any string or superstring theories since they are the solutions of Einstein gravity. As a consequence, they can be considered as various string backgrounds. A natural question thus is to ask if these backgrounds are stable. First thing in this direction will be to check if string/superstring propagating in these backgrounds contain tachyons in their fluctuation spectrum. The aim of this section is to carry out an analysis of this issue. In general, string fluctuations in a non-trivial background is hard to analyse. This is because one needs to have a description of the background in terms of world-sheet conformal field theory (CFT). The dipole backgrounds that we have discussed earlier have very complicated field configurations. However, at very large radial distance the the structure simplifies. Fortunately for us, in this regime, the two dimensional CFT is known and has been analysed in the literature [11]. We will thus make use of his results.

As an illustrative example, we will work with the solution (4) for $D = 5$. The solution can be read off from (4). Various parameters are

$$\Delta = r^2 - 2Mr - a^2, \quad r_0 = M + \sqrt{M^2 + a^2}. \tag{24}$$

Here as before r_0 corresponds to the zero of Δ. For our present purpose, we will also need the periods of X and ϕ. Their ranges are

$$0 \le X \le \frac{4\pi M(M + \sqrt{M^2 + a^2})}{\sqrt{M^2 + a^2}}, \quad 0 \le \phi \le \frac{2\pi a}{\sqrt{M^2 + a^2}}. \tag{25}$$

In order to proceed, we first notice that for $r \to \infty$, the metric reduces to

$$dS^2 = -dt^2 + d\rho^2 + dz^2 + \rho^2 d\phi^2 + dX^2. \tag{26}$$

Here we have defined $\rho = r\sin\theta, z = r\cos\theta$. Thus the metric is flat. However, due to nontrivial periods of various coordinates (25), there is an asymptotic magnetic field B given by

$$B = \frac{a}{\sqrt{M^2 + a^2}}. \tag{27}$$

Upon reduction over X, we would thus get four dimensional Melvin solution (see [12] for detail).

Fortunately, Melvin background is one of the very few backgrounds where string world-sheet has a description in terms of CFT [11][10]. If we denote the radius of X by R (which follows from (25)), then for integer $\frac{1}{BR}$, one has an orbifold CFT. The non-trivial part of the CFT is a Z_N orbifold of 2-dimensional plane times a circle, where N is related to the magnetic field of the Melvin solution. However, it is known that this CFT description for string or superstring, contains tachyon in the spectrum and the mass formula is given by $\alpha' m^2 = -4 + \frac{4}{N}$ [13]. From this observation, we thus conclude that the dipole solution for $D = 5$ at large radial distance leeds to unstable string or superstring background due to the presence of tachyon. We do not see any immediate complications to generalise this result for $D > 5$.

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